Patent
Docket No. 58559US005

DIFFRACTIVE LENS OPTICAL DESIGN

CROSS REFERENCE TO RELATED APPLICATION

This application claims the benefit under 35 USC §119(e) of U.S. Provisional Application No. 60/451,963 filed March 5, 2003, the contents of which in its entirety is hereby incorporated by reference.

FIELD OF THE INVENTION

This invention relates to optical designs employing diffractive surfaces and, in particular, to optical designs employing diffractive surfaces for use in head-mounted display systems.

BACKGROUND OF THE INVENTION

Optical systems for use in head-mounted display systems preferably have the following features:

(1) a sufficiently long eye relief to allow for comfortable viewing by a user wearing eyeglasses;

(2) a sufficiently large exit pupil to minimize restrictions on placement of the observer's eye; and

(3) a sufficiently large field of view to provide a comfortably magnified image of the system's microdisplay.

In addition, it is also desirable for the optical system to be light in weight and to fit into an overall package which can be comfortably worn by the user.

Most frequently the microdisplay used in a head-mounted display system is a LCD light valve device. To assure maximum contrast of the image for this type of device, the optical system used to produce a magnified image of the microdisplay is preferably telecentric on its short conjugate side, i.e., the side where the microdisplay is located.

As known in the art, telecentric lenses are lenses which have at least one pupil at infinity. In terms of principal rays, having a pupil at infinity means that the principal rays are parallel to the optical axis (a) in object space, if the entrance pupil is at infinity, or (b) in image space, if the exit pupil is at infinity.

In practical applications, a telecentric pupil need not actually be at infinity since a lens having an entrance or exit pupil at a sufficiently large distance from the lens' optical surfaces will in essence operate as a telecentric system. The principal rays for such a lens will be substantially parallel to the optical axis and thus the lens will in general be functionally equivalent to a lens for which the theoretical (Gaussian) location of the pupil is at infinity.

Accordingly, as used herein, the terms "telecentric" and "telecentric lens" are intended to include lenses which have a pupil at a long distance from the lens' elements, and the term "telecentric pupil" is used to describe such a pupil at a long distance from the lens' elements. For the lens systems of the invention, the telecentric pupil distance will in general be at least about two times the lens' focal length.

SUMMARY OF THE INVENTION

In accordance with a first aspect, the invention provides an optical system comprising:

(A) a microdisplay (4); and

(B) a magnifier (10) for producing a magnified image of the microdisplay (4) for viewing by a human eye, said magnifier having a focal length f_0, a long conjugate side in the direction of the human eye, a short conjugate side in the direction of the microdisplay, and an f-number f# for light passing from the long conjugate to the short conjugate, said magnifier, in order from the long conjugate side to the short conjugate side, comprising:

(I) a first element (1) having a first surface (S1) which is convex in the direction of the long conjugate, said first element having a focal length f_1;

(II) a block (3) of optical material; and

(III) a second element (2) having a second surface (S2) which is convex in the direction of the short conjugate, said second element having a focal length f_2;

wherein:

(a) $f_1 > 0$;

(b) $f_2 > 0$;

(c) the first surface (S1) is a diffractive surface, or the second surface (S2) is a diffractive surface, or the magnifier (10) comprises a diffractive surface which is separate from the first and second surfaces;

(d) axial light passing through the optical system from the long conjugate to the short conjugate and converging at the microdisplay has a beam diameter at the diffractive surface whose maximum value is d; and

(e) the beam diameter value d, the focal length f_0, and the f-number satisfy the relationship:

$$(f\#\bullet d)/f_0 > 0.4 \text{ (preferably, } (f\#\bullet d)/f_0 > 0.8).$$

In accordance with a second aspect, the invention provides an optical system comprising:

(A) a microdisplay (4); and

(B) a magnifier (10) for producing a magnified image of the microdisplay (4) for viewing by a human eye, said magnifier having a focal length f_0, a long conjugate side in the direction of the human eye, and a short conjugate side in the direction of the microdisplay, said magnifier, in order from the long conjugate side to the short conjugate side, comprising:

(I) a first element (1) having a first surface (S1) which is convex in the direction of the long conjugate, said first element having a focal length f_1;

(II) a block (3) of optical material; and

(III) a second element (2) having a second surface (S2) which is convex in the direction of the short conjugate, said second element having a focal length f_2;

wherein:

(a) $f_1 > 0$;

(b) $f_2 > 0$;

(c) $f_1/f_2 > 1.0$; and

(d) the first surface (S1) is a diffractive surface, or the second surface (S2) is a diffractive surface, or the magnifier comprises a diffractive surface which is separate from the first and second surfaces.

In accordance with a third aspect, the invention provides an optical system comprising:

(A) a microdisplay (4); and

(B) a magnifier (10) for producing a magnified image of the microdisplay (4) for viewing by a human eye, said magnifier having a focal length f_0, a long conjugate side in the direction of the human eye, and a short conjugate side in the direction of the microdisplay, said magnifier, in order from the long conjugate side to the short conjugate side, comprising:

(I) a first element (1) having a first surface (S1) which is convex in the direction of the long conjugate, said first element having a focal length f_1;

(II) a block (3) of optical material; and

(III) a second element (2) having a second surface (S2) which is convex in the direction of the short conjugate, said second element having a focal length f_2;

wherein:

(a) $f_1 > 0$;

(b) $f_2 > 0$;

(c) $f_1/f_0 > 1.3$; and

(d) the first surface (S1) is a diffractive surface, or the second surface (S2) is a diffractive surface, or the magnifier comprises a diffractive surface which is separate from the first and second surfaces.

In accordance with a fourth aspect, the invention provides an optical system comprising:

(A) a microdisplay (4); and

(B) a magnifier (10) for producing a magnified image of the microdisplay (4) for viewing by a human eye, said magnifier having a long conjugate side in the direction of the human eye, a short conjugate side in the direction of the microdisplay, and, in order from the long conjugate side to the short conjugate side, comprises:

(I) a first element (1) having a first surface (S1) which is convex in the direction of the long conjugate, said first element having a focal length f_1;

(II) a block (3) of optical material; and

(III) a second element (2) having a second surface (S2) which is convex in the direction of the short conjugate, said second element having a focal length f_2;

wherein:

(a) $f_1 > 0$;

(b) $f_2 > 0$; and

(c) the magnifier comprises a diffractive surface which is closer to the magnifier's long conjugate side than to its short conjugate side.

Preferably, the first surface (S1) is the diffractive surface.

The reference symbols used in the above summaries of the various aspects of the invention are only for the convenience of the reader and are not intended to and should not be interpreted as limiting the scope of the invention. More generally, it is to be understood that both the foregoing general description and the following detailed description are merely exemplary of the invention, and are intended to provide an overview or framework for understanding the nature and character of the invention.

Additional features and advantages of the invention are set forth in the detailed description which follows, and in part will be readily apparent to those skilled in the art from that description or recognized by practicing the invention as described herein. The accompanying drawings are included to provide a further understanding of the invention, and are incorporated in and constitute a part of this specification.

BRIEF DESCRIPTION OF THE DRAWINGS

Figures 1 through 3 are schematic side views of representative optical systems constructed in accordance with the invention. Figure 1 generally shows the structure of Examples 1A-1F, while Figures 2 and 3 show the structure of Examples 2 and 3, respectively.

The reference numbers used in the figures correspond to the following:

1 first element

2 second element

3 block of optical material

4 microdisplay

5 aperture stop (pupil of user's eye)

6 axial beam

10 magnifier

DESCRIPTION OF THE PREFERRED EMBODIMENTS

As discussed above, the present invention provides optical systems for use in, for example, head-mounted display systems. Examples of the types of systems in which the present invention can be used can be found in Spitzer, U.S. Patent No. 6,384,982 entitled "Compact Image Display System for Eyeglasses or Other Head-Borne Frames," the contents of which are incorporated herein by reference.

In certain embodiments, the magnifier portion of the optical system of the invention comprises two positive elements separated by a block of optical material. In certain preferred embodiments, the magnifier portion consists of just the two positive elements and the block of optical material.

The block of optical material can be cemented to one or both of the positive optical elements. Alternatively, the block of optical material and one or both of the positive optical elements can be formed (e.g., molded) as one solid piece. Forming the entire optical system as a single component can greatly simplify the process of assembling head-mounted display systems during production.

The block of optical material between the positive optical elements is used to lengthen the separation between the elements by a factor proportional to the index of refraction of the material making up the block. This is done to produce an optical system suitable for packaging in a head-mounted display system. To fit various packaging requirements, the optical path through the solid block can be folded.

To minimize the overall weight of the optics, all the optical components, i.e., the first and second elements and the solid block, are preferably made out of plastic, e.g., acrylic.

Aspherical surfaces are used to correct monochromatic aberrations and a diffractive surface is used to provide color correction without the need to include additional elements in the system. For example, each of the positive elements can include an aspheric surface and one of the positive elements can include a diffractive surface. The diffractive surface can also be aspheric if desired.

For systems in which the positive elements are separate components, the aspheric and diffractive surfaces can be on either side of the element, i.e., the side facing the long conjugate end or the short conjugate end of the optical system. When a positive element is combined with the solid block of optical material, the free surface of the element (i.e., the surface not combined with the block) will be either aspheric or aspheric and diffractive. The diffractive surface can be formed on an end surface of the solid block of optical material for systems in which the solid block has a free end surface.

The diffractive surface can be used on either of the positive elements or on either free end surface of the block of optical material for a block having two free end surfaces. Ghosting associated with secondary images in parasitic diffraction orders is minimized when the diffractive surface is farther away from the microdisplay. Thus, a preferred location for the diffractive surface is the element or free surface of the block of optical material that will be closest to the observer's eye during use of the head-mounted display system. For systems in which the positive elements and the solid block are a single component, the diffractive surface is preferably at the end of the component farthest from the microdisplay.

The system preferably includes only one diffractive surface since the presence of multiple diffractive surfaces can result in diffractive interactions which will degrade the image provided to the user.

Without intending to limit it in any manner, the present invention will be more fully described by the following examples.

EXAMPLES

The following Examples 1A-1F, 2, and 3 illustrated optical systems suitable for use in head-mounted display systems where the optical system has the following characteristics:

(1) a field of view of 18°, which corresponds to seeing a 12.5 inch diagonal image at 1 meter away from the viewer;

(2) an exit pupil diameter of 6.0 millimeters for light traveling from the microdisplay to the user's eye; and

(3) an eye relief distance of 25.0 millimeters.

The aspheric coefficients set forth in the prescription tables for Examples 1A-1F, 2, and 3 are for use in the following equation:

$$z = \frac{cy^2}{1+[1-(1+k)c^2y^2]^{1/2}} + Dy^4 + Ey^6 + Fy^8 + Gy^{10} + Hy^{12} + Iy^{14}$$

where z is the surface sag at a distance y from the optical axis of the system, c is the curvature of the surface at the optical axis, and k is a conic constant, which is zero except where indicated in the prescriptions of Tables 1A-1F, 2, and 3.

The designation "a" associated with various surfaces in the tables represents a surface for which at least one of D, E, F, G, H, or I in the above equation is not zero; and the designation "c" indicates a surface for which k in the above equation is not zero. As used in the claims, an aspheric surface is a surface for which at least one of k, D, E, F, G, H, or I is not zero. The designation "p" used with various of the surfaces in the tables represents a diffractive (phase) surface.

The prescription tables are constructed on the assumption that light travels from left to right in the figures. In actual practice, the user's eye will be on the left and the microdisplay will be on the right, and light will travel from right to left. In particular, the references in the prescription tables to objects/images and entrance/exit pupils are reversed from that used in the rest of this application. All dimensions given in the prescriptions and in Table 4 below are in millimeters. Surface 7 in the prescriptions of Examples 1A-1F, surface 6 in the prescription of Example 2, and surface 8 in the prescription of Example 3 is the cover glass of the microdisplay (imager). Surface 6 in Example 3 is a polarizer used with the imager. The index of refraction and dispersion of the block of optical material in Example 3 is given in standard six digit form, i.e., abcxyz, where n = 1.abc and v = xy.z.

The diffractive is formed on surface 5 in Examples 1A-1D, and on surface 2 in Examples 1E-1F, 2, and 3. For Examples 1A-1D, the characteristics of the diffractive surface in ZEMAX terminology are: diff order: 1, scaling (normalized) rad ap: 10, and quadratic phase term: -1907.1553; while for Examples 1E and 3, the characteristics are: diff order: 1, scaling (normalized) rad ap: 10, and P2 & P4 phase terms: -800.0 & 100.0, respectively; and for Examples 1F and 2, the characteristics are: diff order: 1, scaling (normalized) rad ap: 10, and P2 & P4 phase terms: -1200.0 & 100.0, respectively.

The focal lengths and selected other properties of the elements making up the magnifiers of Examples 1A-1F, 2, and 3 are set forth in Table 4, where f_0 is the focal length of the system, f_1 is the focal length of the element closest to the user's eye, f_2 is the focal length of the element closest to the microdisplay, BFL is the paraxial back focal distance at infinity not including the faceplate of the microdisplay, i.e., the distance from the element closest to the microdisplay to the focal plane for light traveling from left to right in the figures, and d is the diameter of the axial beam at the diffractive surface.

As to "T", this parameter is the distance between the first and last optical surfaces of the optical system. To achieve a preferred packaging configuration for a head-mounted display system, it is desirable to separate the components of the optical system by about 30 mm to 35 mm, which is approximately the distance between the optical axis of a user's eye and his or her corresponding temple. Hence, the overall distance between the first and the last surface of the optical system is preferably larger than 30 mm. On the other hand, so that the optical system is not overly long, T is preferably less than 45 mm.

As can be seen from Table 4, f_0, f_1, and f_2 preferably satisfy the following relationships:

$$f_1/f_2 > 1.0; \text{ and/or}$$

$$f_1/f_0 > 1.3.$$

For the diffractive surface to be effective in terms of chromatic aberration correction, the minimum diameter of the axial beam at the diffractive surface preferably satisfies the following relationship:

$$(f\#\bullet d)/f_0 > 0.4,$$

where f# is the f-number of the optical system, i.e., the focal length f_0 divided by the entrance pupil diameter for light traveling from the long conjugate towards the short conjugate. For each of Examples 1A-1F, 2, and 3, the f# is 5. Most preferably, the diffractive surface is located at a position so that the $(f\#\bullet d)/f_0$ ratio is greater than 0.8.

Although specific embodiments of the invention have been described and illustrated, it is to be understood that a variety of modifications which do not depart from the scope and spirit of the invention will be evident to persons of ordinary skill in the art from the foregoing disclosure.

TABLE 1A

Surf. No.	Type	Radius	Thickness	Glass	Clear Aperture Diameter
1		Aperture stop	25.00000		6.09
2	ac	23.2851	5.00000	ACRYLIC	14.29
3		∞	28.00000	ACRYLIC	14.28
4		∞	0.50000		14.22
5	p	∞	5.00000	ACRYLIC	14.22
6	a	-21.0877	11.70000		14.30
7		∞	1.00000	BSC7	10.20
8		∞	-0.01315		10.00

Symbol Description

a - Polynomial asphere
c - Conic section
p - Phase surface

Even Polynomial Aspheres and Conic Constants

Surf. No.	k	D	E	F
2	-1.0000E+00	1.8457E-05	-1.1805E-06	3.2326E-08
6		1.1792E-04	-1.9097E-06	3.9462E-08

Surf. No.	G	H	I
2	-2.9215E-10	-1.9562E-12	3.4875E-14
6	-4.0048E-10	4.3344E-13	1.5072E-14

First Order Data

f/number	5.00	Overall Length	-923.851
Magnification	0.0305	Forward Vertex Distance	76.1868
Object Height	160.00	Barrel Length	76.2000
Object Distance	1000.04	Entrance Pupil Distance	0.00
Effective Focal Length	30.0003	Exit Pupil Distance	59.8232
Image Distance	-.131546E-01	Stop Diameter	6.093
Stop Surface Number	1	Distance to Stop	0.00

First Order Properties of Elements

Element Number	Surface Numbers	Power	f'
1	2 3	0.21206E-01	47.157
3	5 6	0.26471E-01	37.778

TABLE 1B

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Surf. No.	Type	Radius	Thickness	Glass	Clear Aperture Diameter
1		Aperture stop	25.00000		6.09
2	ac	23.3136	5.00000	ACRYLIC	14.29
3		∞	28.00000	ACRYLIC	14.28
4		∞	0.50000		14.24
5	p	∞	5.00000	ACRYLIC	14.24
6	a	-21.0877	11.73460		14.11
7		∞	1.00000	BSC7	10.15
8		∞	0.00420		9.95

Symbol Description

a - Polynomial asphere
c - Conic section
p - Phase surface

Even Polynomial Aspheres and Conic Constants

Surf. No.	k	D	E	F
2	-1.0000E+00	1.4796E-05	-9.7462E-07	3.1044E-08
6		1.1792E-04	-1.9097E-06	3.9462E-08

Surf. No.	G	H	I
2	-3.3642E-10	-2.0677E-12	4.4089E-14
6	-4.0048E-10	4.3344E-13	1.5072E-14

First Order Data

f/number	5.00	Overall Length	-924.045
Magnification	0.0305	Forward Vertex Distance	76.2388
Object Height	160.00	Barrel Length	76.2346
Object Distance	1000.28	Entrance Pupil Distance	0.00
Effective Focal Length	30.0078	Exit Pupil Distance	59.8511
Image Distance	0.419694E-02	Stop Diameter	6.095
Stop Surface Number	1	Distance to Stop	0.00

First Order Properties of Elements

Element Number	Surface Numbers	Power	f'
1	2 3	0.21180E-01	47.215
3	5 6	0.26471E-01	37.778

TABLE 1C

Surf. No.	Type	Radius	Thickness	Glass	Clear Aperture Diameter
1		Aperture stop	25.00000		6.09
2	ac	23.2851	3.50000	ACRYLIC	14.29
3		∞	31.00000	ACRYLIC	14.28
4		∞	0.65000		14.22
5	p	∞	3.50000	ACRYLIC	14.22
6	a	-21.0877	11.70000		14.09
7		∞	1.00000	BSC7	10.13
8		∞	-0.00967		10.00

Symbol Description

a - Polynomial asphere
c - Conic section
p - Phase surface

Even Polynomial Aspheres and Conic Constants

Surf. No.	k	D	E	F
2	-1.0000E+00	1.8457E-05	-1.1805E-06	3.2326E-08
6		1.1792E-04	-1.9097E-06	3.9462E-08

Surf. No.	G	H	I
2	-2.9215E-10	-1.9562E-12	3.4875E-14
6	-4.0048E-10	4.3344E-13	1.5072E-14

First Order Data

f/number	5.00	Overall Length	-927.210
Magnification	0.0305	Forward Vertex Distance	76.3403
Object Height	160.00	Barrel Length	76.3500
Object Distance	1003.55	Entrance Pupil Distance	0.00
Effective Focal Length	30.1001	Exit Pupil Distance	59.3244
Image Distance	-.967404E-02	Stop Diameter	6.115
Stop Surface Number	1	Distance to Stop	0.00

First Order Properties of Elements

Element Number	Surface Numbers		Power	f'
1	2	3	0.21206E-01	47.157
3	5	6	0.26549E-01	37.667

TABLE 1D

Surf. No.	Type	Radius	Thickness	Glass	Clear Aperture Diameter
1		Aperture stop	25.00000		6.09
2	ac	23.3136	3.50000	ACRYLIC	14.29
3		∞	31.00000	ACRYLIC	14.28
4		∞	0.65000		14.24
5	p	∞	3.50000	ACRYLIC	14.24
6	a	-21.0877	11.73460		14.11
7		∞	1.00000	BSC7	10.15
8		∞	0.00784		10.00

Symbol Description

a - Polynomial asphere
c - Conic section
p - Phase surface

Even Polynomial Aspheres and Conic Constants

Surf. No.	k	D	E	F
2	-1.0000E+00	1.4796E-05	-9.7462E-07	3.1044E-08
6		1.1792E-04	-1.9097E-06	3.9462E-08

Surf. No.	G	H	I
2	-3.3642E-10	-2.0677E-12	4.4089E-14
6	-4.0048E-10	4.3344E-13	1.5072E-14

First Order Data

f/number	5.00	Overall Length	-927.398
Magnification	0.0305	Forward Vertex Distance	76.3924
Object Height	160.00	Barrel Length	76.3846
Object Distance	1003.79	Entrance Pupil Distance	0.00
Effective Focal Length	30.1075	Exit Pupil Distance	59.3507
Image Distance	0.783791E-02	Stop Diameter	6.116
Stop Surface Number	1	Distance to Stop	0.00

First Order Properties of Elements

Element Number	Surface Numbers	Power	f'
1	2 3	0.21180E-01	47.215
3	5 6	0.26549E-01	37.667

TABLE 1E

Surf. No.	Type	Radius	Thickness	Glass	Clear Aperture Diameter
1		Aperture stop	25.00000		6.09
2	acp	23.3136	3.50000	ACRYLIC	14.29
3		∞	31.00000	ACRYLIC	14.28
4		∞	0.65000		14.30
5		∞	3.50000	ACRYLIC	14.24
6	a	-21.0877	11.10000		14.11
7		∞	1.00000	BSC7	10.15
8		∞	0.02818		10.00

Symbol Description

a - Polynomial asphere
c - Conic section
p - Phase surface

Even Polynomial Aspheres and Conic Constants

Surf. No.	k	D	E	F
2	-1.0000E+00	1.4796E-05	-9.7462E-07	3.1044E-08
6		1.1792E-04	-1.9097E-06	3.9462E-08

Surf. No.	G	H	I
2	-3.3642E-10	-2.0677E-12	4.4089E-14
6	-4.0048E-10	4.3344E-13	1.5072E-14

First Order Data

f/number	5.00	Overall Length	-956.598
Magnification	0.0305	Forward Vertex Distance	75.7782
Object Height	160.00	Barrel Length	75.7500
Object Distance	1032.38	Entrance Pupil Distance	0.00
Effective Focal Length	31.0579	Exit Pupil Distance	75.7006
Image Distance	0.281843E-01	Stop Diameter	6.290
Stop Surface Number	1	Distance to Stop	0.00

First Order Properties of Elements

Element Number	Surface Numbers		Power	f'
1	2	3	0.22570E-01	44.306
3	5	6	0.23415E-01	42.707

TABLE 1F

Surf. No.	Type	Radius	Thickness	Glass	Clear Aperture Diameter
1		Aperture stop	25.00000		6.09
2	acp	23.3136	3.50000	ACRYLIC	14.29
3		∞	31.00000	ACRYLIC	14.28
4		∞	0.65000		14.30
5		∞	3.50000	ACRYLIC	14.24
6	a	-21.0877	10.50000		14.11
7		∞	1.00000	BSC7	10.15
8		∞	-0.02904		10.00

Symbol Description

a - Polynomial asphere
c - Conic section
p - Phase surface

Even Polynomial Aspheres and Conic Constants

Surf. No.	k	D	E	F
2	-1.0000E+00	1.4796E-05	-9.7462E-07	3.1044E-08
6		1.1792E-04	-1.9097E-06	3.9462E-08

Surf. No.	G	H	I
2	-3.3642E-10	-2.0677E-12	4.4089E-14
6	-4.0048E-10	4.3344E-13	1.5072E-14

First Order Data

f/number	5.00	Overall Length	-948.861
Magnification	0.0305	Forward Vertex Distance	75.1210
Object Height	160.00	Barrel Length	75.1500
Object Distance	1023.98	Entrance Pupil Distance	0.00
Effective Focal Length	30.7991	Exit Pupil Distance	73.8276
Image Distance	-.290390E-01	Stop Diameter	6.239
Stop Surface Number	1	Distance to Stop	0.00

First Order Properties of Elements

Element Number	Surface Numbers		Power	f'
1	2	3	0.23266E-01	42.982
3	5	6	0.23415E-01	42.707

TABLE 2

Surf. No.	Type	Radius	Thickness	Glass	Clear Aperture Diameter
1		Aperture stop	25.00000		6.09
2	acp	23.3136	3.50000	ACRYLIC	14.29
3		∞	31.00000	ACRYLIC	14.28
4		∞	3.50000	ACRYLIC	14.24
5	a	-21.0877	10.50000		14.11
6		∞	1.00000	BSC7	10.15
7		∞	0.31123		10.00

Symbol Description

a - Polynomial asphere
c - Conic section
p - Phase surface

Even Polynomial Aspheres and Conic Constants

Surf. No.	k	D	E	F
2	-1.0000E+00	1.4796E-05	-9.7462E-07	3.1044E-08
5		1.1792E-04	-1.9097E-06	3.9462E-08

Surf. No.	G	H	I
2	-3.3642E-10	-2.0677E-12	4.4089E-14
5	-4.0048E-10	4.3344E-13	1.5072E-14

First Order Data

f/number	5.00	Overall Length	-937.929
Magnification	0.0305	Forward Vertex Distance	74.8112
Object Height	160.00	Barrel Length	74.5000
Object Distance	1012.74	Entrance Pupil Distance	0.00
Effective Focal Length	30.4668	Exit Pupil Distance	74.4743
Image Distance	0.311233	Stop Diameter	6.171
Stop Surface Number	1	Distance to Stop	0.00

First Order Properties of Elements

Element Number	Surface Numbers		Power	f'
1	2	3	0.23266E-01	42.982
3	4	5	0.23415E-01	42.707

TABLE 3

Surf. No.	Type	Radius	Thickness	Glass	Clear Aperture Diameter
1		Aperture stop	25.00000		6.55
2	acp	23.3136	3.50000	ACRYLIC	14.38
3		∞	34.00000	533558	14.33
4		∞	3.50000	ACRYLIC	13.71
5	a	-21.0877	7.67000		13.66
6		∞	1.00000	BSC7	11.12
7		∞	2.60000		10.94
8		∞	0.70000	BSC7	10.21
9		∞	0.00187		10.09

Symbol Description

a - Polynomial asphere
c - Conic section
p - Phase surface

Even Polynomial Aspheres and Conic Constants

Surf. No.	k	D	E	F
2	-1.0000E+00	1.4796E-05	-9.7462E-07	3.1044E-08
5		1.1792E-04	-1.9097E-06	3.9462E-08

No.	G	H	I
2	-3.3642E-10	-2.0677E-12	4.4089E-14
5	-4.0048E-10	4.3344E-13	1.5072E-14

First Order Data

f/number	5.00	Overall Length	-967.869
Magnification	0.0305	Forward Vertex Distance	77.9719
Object Height	160.00	Barrel Length	77.9700
Object Distance	1045.84	Entrance Pupil Distance	0.00
Effective Focal Length	31.4555	Exit Pupil Distance	75.2397
Image Distance	0.187063E-02	Stop Diameter	6.372
Stop Surface Number	1	Distance to Stop	0.00

First Order Properties of Elements

Element Number	Surface Numbers	Power	f'
1	2 3	0.22570E-01	44.306
3	4 5	0.23415E-01	42.707

TABLE 4

Ex. No.	f0	f1	f2	T	BFL	d
1A	30.0	47.16	37.78	38.50	13.26	3.00
1B	30.0	47.21	37.78	38.50	13.31	2.97
1C	30.1	47.16	37.67	38.65	13.27	2.82
1D	30.1	47.21	37.67	38.65	13.32	2.83
1E	31.1	44.31	42.71	38.65	12.94	6.12
1F	30.8	42.98	42.71	38.65	12.07	6.24
2	30.5	42.98	42.71	38.00	12.40	6.17
3	31.5	44.31	42.71	41.00	12.35	6.20